ISSN 0005–1144
ATKAAF 45(1–2), 33–39 (2004)

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Single and Multi Element Printed Minkowski Monopole Antennas for Portable Terminal Devices

UDK 621.396.67
IFAC IA 5.8.3;5.8.1

Original scientific paper

In this paper a printed fractal Minkowski monopole is presented for use in wireless terminal devices utilizing single and multi element antenna systems. In the case of a single element system the effect of the antenna's placement with respect to the ground plane is examined and a method to fine tune the system in its worst case situation is proposed. The influence of the ground plane dimensions on the system's impedance and radiation characteristics is also investigated and general conclusions are drawn. Subsequently, a four element antenna system for diversity applications is investigated. The diversity performance is evaluated by means of the envelope correlation coefficient, the mean effective gain and the effective diversity gain. The impact of the mutual coupling on the system's performance is also addressed.

Key words: antenna diversity, diversity gain, fractal antenna, ground plane effect, Minkowski, monopole antenna

1 INTRODUCTION

The rapid evolution of wireless communication technologies in recent years has raised the need for new design concepts in antenna engineering. The decreasing size and weight of the handheld terminal devices, on the one hand, and the necessity for multi element antenna systems on the other, push antenna technology into facing the challenge of designing small but at the same time efficient radiators. For this, an intense research interest has been observed recently in the areas of antenna miniaturization [1] and fractal antennas [2], where fractal concepts have proven to possess great miniaturization ability.

A well known and at no additional cost way to overcome the previously mentioned shortcomings, is by making the already existing terminal device's ground plane an »active« part of the radiating system [3]. This is the fundamental principle of the category of printed monopole antennas that use the ground plane through current induction to produce an asymmetric image of the monopole. It has been shown that by using this concept, the performance of compact fractal monopole antennas can be considerably enhanced in terms of bandwidth, efficiency and gain [4–5]. Although the ground plane is an »active« part of the radiating system, little attention has been paid so far in the way it affects the system's performance [6]. Such an investigation, which is the scope of the second section of the paper, is very interesting especially now where the dimensions of terminal devices decrease dramatically.

The third section of the paper addresses the utilization of the printed Minkowski monopole antenna in the design of a multi-element antenna diversity system. The diversity performance is evaluated by means of the envelope correlation coefficient, the mean effective gain and the effective diversity gain and the impact of the mutual coupling on the performance of the system is also discussed.

2 SINGLE ELEMENT ANTENNA SYSTEM

In this section of the paper an investigation is carried out on how the antenna's placement at different positions, from the center to the corner of the ground plane affects the input impedance characteristics of the antenna system. A simple method to fine tune the system in the worst case is also provided. Furthermore, the effect of the ground plane dimensions on the system's performance is examined in terms of both input impedance and radiation characteristics [7].

2.1 Antenna's placement effect on impedance characteristics

The geometry and dimensions of the configuration under investigation are depicted in Figure 1(a). The single antenna element system consists of two metallic layers with the antenna placed at the upper one and the ground plane at the bottom. The dimensions of the dielectric layer are 45×105 mm^2 with the ground being 45 mm wide and 90 mm long, which are typical for a portable terminal device. The monopole is printed on an 8 mils-thick

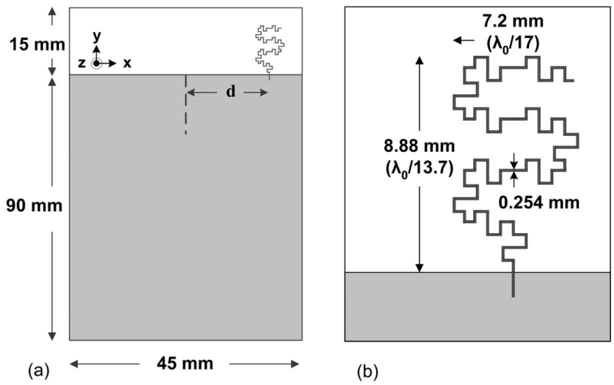


Fig. 1 Geometry and dimensions of the investigated antenna-ground plane system, (a) top view and (b) details of the Minkowski monopole antenna

substrate, with relative permittivity $\varepsilon_r = 3.38$ and loss tangent, $\tan\delta = 0.0027$, while the thickness of the copper layers is 35 μm (1 ounce).

The geometry and dimensions of the compact monopole are illustrated in detail in Figure 1(b). The element is a modified Minkowski monopole operating in the 2.4 GHz ISM band and has been chosen on the grounds of its extremely compact size, due to its high dimensionality, and ease of construction [4]. The trace of the monopole is 0.254 mm (10 mils) wide and has 49 mm overall physical length. It occupies an area of 7.2×8.88 mm^2 (i.e. $\lambda_0/17 \times \lambda_0/13.7$) and is fed by a 50-Ω microstrip line.

The configuration of Figure 1 was simulated using IE3D [8] for different values of the parameter d, which defines the off centre position of the monopole, that was varied from 0 to 21 mm with a 3 mm step. The plots of the resonant frequency, defined by the zero crossing of the reactance curve, and the resistance at resonance versus the off centre displacement are shown in Figure 2.

It can be seen that as the monopole moves away from the centre of the ground plane towards the corner, the resonant frequency decreases from 2.53 to 2.38 GHz (5.9 %), while the input resistance increases from 27 to 63.3 Ω (135 %).

It is interesting to make a comparison of this behavior with that of a vertical monopole mounted at different positions on a cubical conducting box. According to [9], as the vertical monopole moves from the center to the corner of the cubical box the input resistance increases up to 122 %, while the resonant frequency increases up to 4.7 %. Though the modified Minkowski element is not vertically mounted on the ground plane and both the ground and the antenna are planar, the behavior regarding the input resistance is similar, while the resonant frequency follows a reverse pattern.

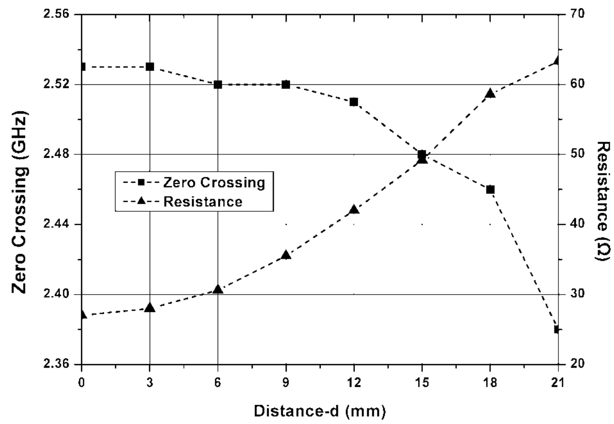


Fig. 2 Zero crossing of the input reactance and corresponding resistance versus the off-center displacement d

A way to fine tune the antenna at the center of the ground plane, is shown in Figure 3, where a slot is introduced at the ground plane near the antenna acting as a stub. The slot has 17 mm

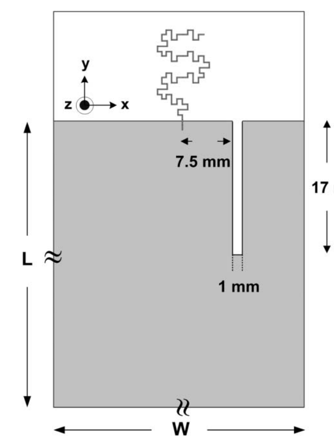


Fig. 3 Geometry and details of the Minkowski monopole placed at the center of the ground plane along with the inserted slot

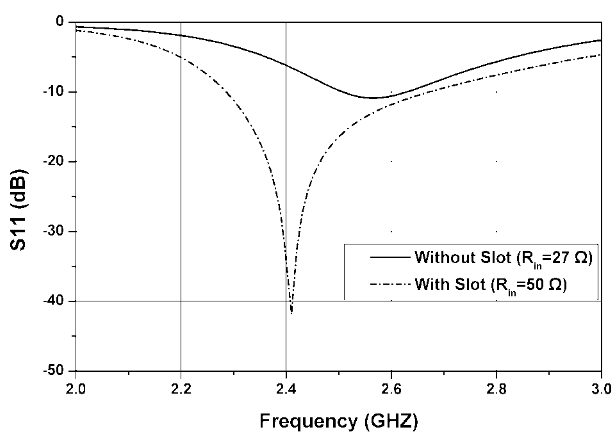


Fig. 4 Input return losses S_{11} and input resistance R_{in} at resonance of the antenna system, with and without the inserted slot

length, 1 mm width and is placed 7.5 mm away from the monopole. Its length and placement were appropriately chosen in order to fine tune the system. The simulated input return losses and the input resistance at resonance of the antenna system with and without the slot are depicted in Figure 4. It can be seen that the configuration with the slot resonates at 2.41 GHz having a 390 MHz bandwidth (16.2 %).

2.2 Ground plane effect on impedance characteristics

In this section the effects of the ground plane dimensions on the performance of the antenna system are examined. The ground plane was varied from 25 to 65 mm with a 5 mm step in width and from 10 to 110 mm with a 10 mm step in length, while the Minkowski monopole was placed 4 mm from the right corner of the ground plane (Figure 1). The simulated results of the resonant frequency, bandwidth and resistance versus the dimensions of the ground plane are depicted in Figures 5–7 respectively. As a first remark it can be inferred that the plots do not follow a general trend as happened with the plots of the previous section and that slight changes of the ground plane dimensions can cause considerable alteration on the system's input impedance characteristics.

When both dimensions of the ground plane are greater than a quarter wavelength (30 mm), the system is well tuned with the resonant frequency rarely shifting above 2.54 GHz (3.5 % shift), the bandwidth rarely dropping below 300 MHz and the resistance being above 44 Ω. The system remains tuned even when one of the dimensions of the ground plane is less than a quarter wavelength so long as the other is greater. The width seems to be more sensitive to shortening than the length as it can be deduced from Figures 6–7 and this can be attributed to the fact that the induced currents are mainly concentrated along the width of the ground and near to the antenna element. In that case it can be seen that the smallest ground that can support a well-tuned system is $L \cdot W = 35 \cdot 10$ mm^2, which corresponds to $\lambda_0^2/43$ area, having a resonance at 2.51 GHz and 170 MHz bandwidth. When both dimensions become smaller than a quarter wavelength then a rapid decay takes place, especially in terms of bandwidth and resistance. The system's efficiency is high in all cases varying from 89 %, when the ground's dimensions are small, to 93 %.

It is clear from the above remarks that the ground plane affects in a different way different antenna elements such as the helix, the PIFA and the Minkowski [6]. This strengthens the fact that it is no longer acceptable to view the antenna as a separate component that could be selected in a late design phase, but as an integrated part that must be designed along with the entire layout of the transceiver.

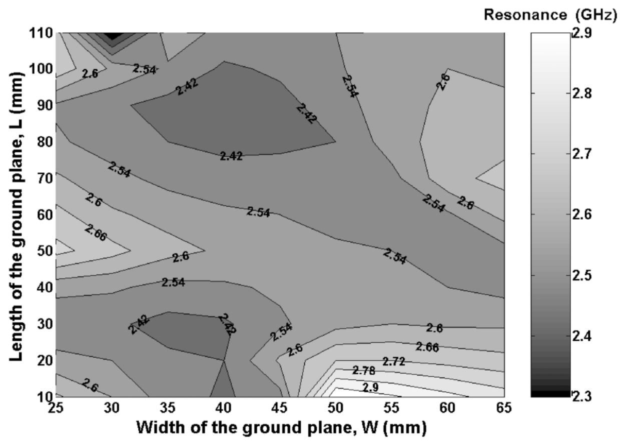


Fig. 5 Effect of the ground plane dimensions on the resonant frequency of the antenna system

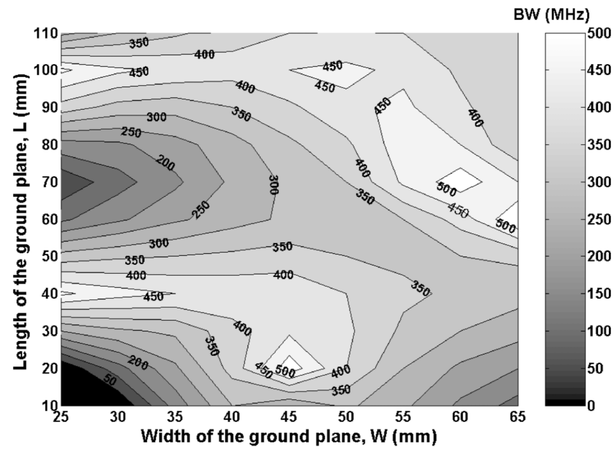


Fig. 6 Effect of the ground plane dimensions on the bandwidth of the antenna system

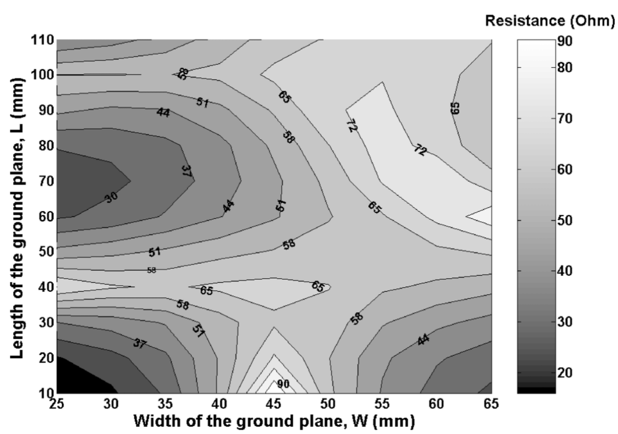
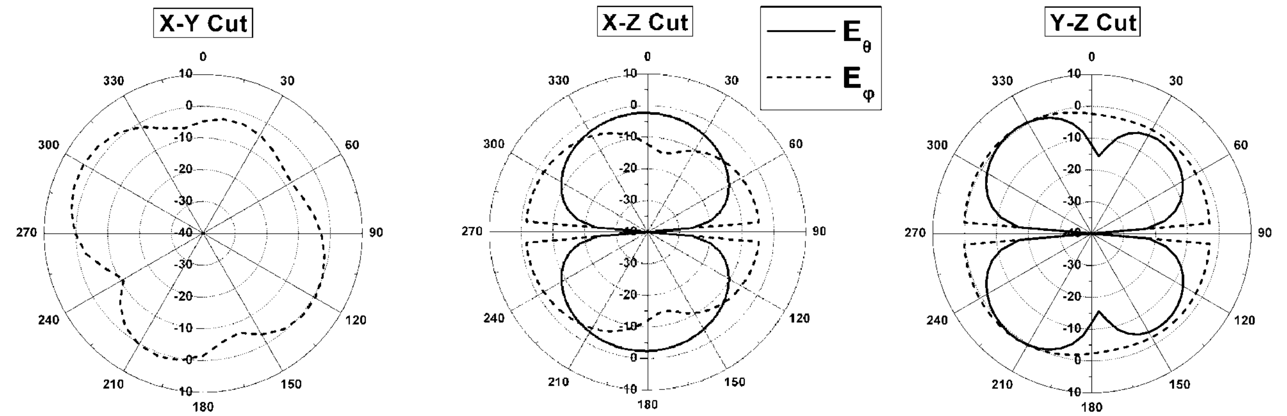
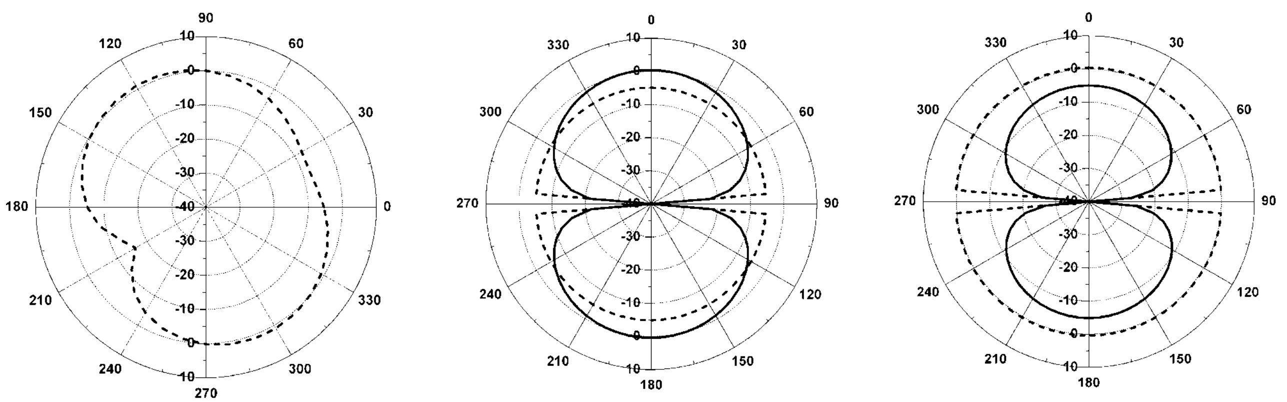


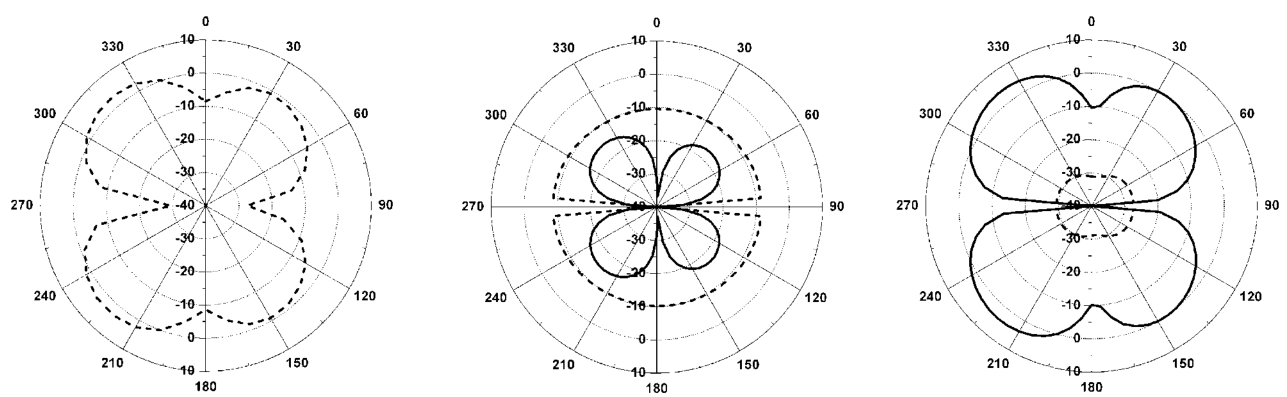
Fig. 7 Effect of the ground plane dimensions on the system's input resistance at resonance



(a)



(b)



(c)

Fig. 8 Computed gain cuts of the Minkowski monopole placed (a) at the corner of the ground plane with L = 90 mm and W = 45 mm, (b) at the corner of the ground plane with L = 10 mm and W = 35 mm and (c) at the center of the ground plane with dimensions L = 90 mm and W = 45 mm

2.3 Ground plane effect on radiation characteristics

The effect of the ground plane's dimensions on the radiation characteristics of the system was also considered. The computed gain patterns of the Minkowski monopole placed at the corner of the ground plane with dimensions $L = 90$ mm, $W = 45$ mm and $L = 10$ mm, $W = 35$ mm are depicted in figures 8(a) and 8(b) respectively. Both E_θ and E_φ components of the electric field are illustrated at the three principal plane cuts ($\theta = 90°$, $\varphi = 0°$, $\varphi = 90°$). It can be observed that as the dimensions of the ground plane decrease the patterns become more uniform and the characteristic rippling of Figure 8(a) vanishes. The directivity decreases from 4.1 dBi in the case of Figure 8(a) to 2.1 dBi in the case of Figure 8(b), approaching the limit of the ideal small dipole which is 1.76 dBi. Moreover, it can be seen that in both cases the polarization is elliptical since the components of the electric field for the X-Z and Y-Z cuts are of the same magnitude. This can be mainly attributed to the asymmetric placement of the monopole with respect to the ground plane, rather than to the geometry of the monopole. To verify this, the gain pattern of a Minkowski monopole placed at the center of the ground plane with dimensions $L = 90$ mm, $W = 45$ mm is illustrated in Figure 8(c). The gain cuts resemble that of a straight printed dipole antenna, the cross-polar components are essentially reduced, whereas the rippling is attributed to the great size of the ground plane. By reducing the dimensions of the ground an almost identical pattern to the straight printed monopole can be achieved.

3 MULTI ELEMENT ANTENNA SYSTEM

The printed Minkowski monopole antenna has been already used for the realization of a two [4] and a three-element [10] antenna diversity system. In this section a four-element configuration is investigated comprising four equally spaced Minkowski monopoles operating in the 2.4 GHz ISM band [11]. According to Section 2.1, a $\lambda/4$ slot between elements 2 and 3 is introduced, as shown in Figure 9, in order to increase the impedance of the adjacent inner pair of monopoles. In Figure 10 the return loss Sii of each antenna element is illustrated exhibiting sufficiently large bandwidths in the order of 9 %. The gain patterns of the radiating elements at the azimuth plane are depicted in Figure 11. Due to the complementary performance of the four antennas, the configuration exhibits a hybrid space – pattern diversity with omni directional antennas.

The diversity performance of a multi-element antenna system depends on the cross correlation

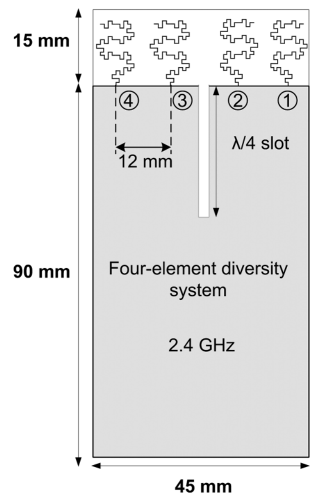


Fig. 9 The geometry of the four element antenna diversity system

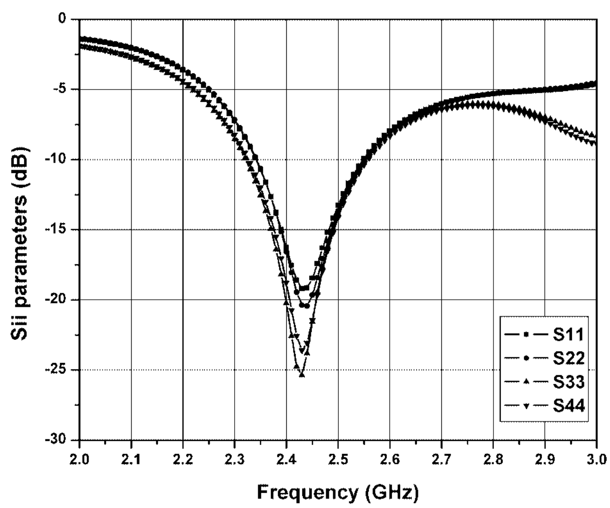


Fig. 10 The Sii parameters of the four element configuration

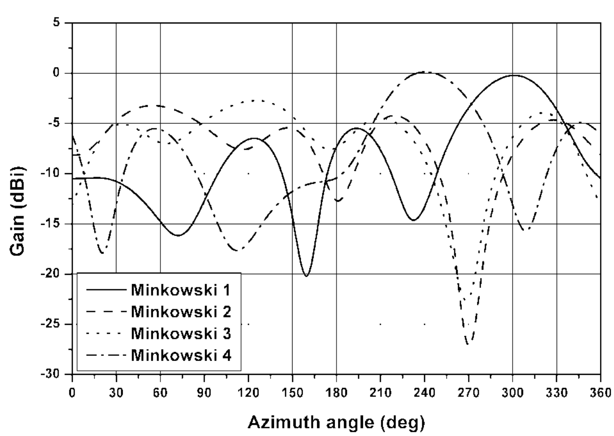


Fig. 11 Antenna gain patterns at the azimuth plane for the four element diversity system

and the relative mean power levels between the signals delivered from each antenna branch. These two factors comprise the essential criteria, which need to be fulfilled in order to achieve diversity gain [12]:

$$\rho_{eij} < 0.5 \quad \text{and} \quad P_i \cong P_j \tag{1}$$

where ρ_e is the envelope correlation coefficient and P the mean power level $(i, j = 1, 2, 3, 4)$. Assuming that the mean incident power on each antenna is the same, the equality criterion between P_i and P_j reduces to equality between MEG_i and MEG_j [13].

In this paper the diversity performance of the investigated system is quantified by means of the effective diversity gain (EDG) [14] which is computed as a function of the envelope correlation coefficient and mean effective gain for the maximum ratio combining case at 1 % outage probability [15].

The calculated envelope correlation coefficients and the MEG ratios between the Minkowski monopoles as well the effective diversity gain are depicted in Table 1, where it can be deduced that the diversity conditions (1) are easily satisfied. The MEG ratios between the antennas are very close to unity, indicating that the mean power delivered from each antenna branch is the same, ρ_e is in most cases far below 0.5, whereas the system exhibits an EDG of 9.2 dB.

Table 1 **The envelope correlation coefficients, the MEG ratios of the Minkowski monopoles and the effective diversity gain of the four-element system**

Monopoles	ρ_e	MEG ratio	EDG (dB)
1–2	0.081	1.016	9.278
1–3	0.424	0.933	
1–4	0.046	0.915	
3–4	0.073	0.918	

It should be mentioned that the low values of ρ_e are attributed to the mutual coupling between the closely spaced antenna elements with their inter-element spacing playing a key role to the decorrelation mechanism. According to [12], for inter-element spacing less than $0.4\,\lambda$ the electrical separation (χ) exhibits higher values than the physical separation (d) allowing the antennas to be placed even closer. In the examined case, the physical separation of the Minkowski monopoles is $d = 0.1\,\lambda$ (12 mm), which corresponds to an electrical separation of $\chi = 0.2\lambda$ (24 mm) providing thus low values of ρ_e.

Mutual coupling, besides its beneficial decorrelation effect, results in a reduction of the efficiency and the MEG of the antennas deteriorating their individual performance. Table 2 illustrates the MEG and the efficiency of the Minkowski monopoles for different multi-element diversity systems where it can be easily concluded that increasing the number of elements results in a decrease of the antennas' MEG and efficiency. This fact should not lead to the false conclusion that the increase of the antennas results in the deterioration of the system's performance. On the contrary, MEA systems exhibit superior performance in comparison with the single element configurations. This is attributed to the fact that combining techniques sum the uncorrelated signals received from each antenna branch resulting in a higher received SNR even if the MEG of each antenna is lower. On the other hand, although the reduced antenna efficiencies increase the power consumption, this effect is compensated by the fact that diversity systems offer higher data rates, which reduce the receiver's duty cycle.

Table 2 **MEG and efficiency of the Minkowski monopoles and the effective diversity gain under MRC at 1 % outage probability of different multi element systems**

No. of elements	efficiency (%)	MEG (dBi)	EDG (dB)
1	93	−4.07	–
2	80, 80	−4.76, −4.76	7
3	75, 65, 75	−4.80, −5.99, −4.80	11.05
4	30, 33, 28, 30	−8.98, −9.05, −8.68, −8.60	9.278

The EDG values of different systems illustrated in Table 2 prove the superior performance of the multi-element systems in comparison with the single element configuration. However, it can be observed that the three-element system exhibits higher value of EDG relative to the examined case, making thus, the pursuit of more than three Minkowski elements in a device with the ground plane of Figure 9 unnecessary for the 2.4 GHz band.

4 CONCLUSIONS

The effect of the placement of a compact Minkowski monopole antenna on top of a typical terminal device's ground plane has been investigated. It has been shown that as the element moves from the centre of the ground to the corner the resonant frequency decreases, whereas the input resistance increases. In the case of the monopole being mounted at the centre of the ground, a slot acting as a stub has been proposed to fine-tune the antenna to the band of interest.

The role of the ground plane dimensions on the system's input impedance and radiation characteristics has been also examined. The system remains well tuned when both dimensions of the ground plane are greater than a quarter wavelength, whereas the width proved to be more sensitive to shortening. The directivity of the system decreases when the dimensions of the ground plane decrease and the patterns become more uniform. The polarization is mainly determined by the placement of the monopole with respect to the ground plane, while the efficiency is high in all cases.

Due to the compact size and favourable characteristics of the Minkowski monopole, a four element diversity system in the 2.4 GHz ISM band was also considered. The diversity conditions were easily fulfilled providing an effective diversity gain of 9.3 dB. The beneficial impact of mutual coupling on the envelope correlation coefficient as well as the reduction effect on MEG and efficiency of the antennas were observed. The above parameters were summarized leading to the conclusion that the type of the antennas, their placement and their electrical distance are key parameters in the design of an efficient multi element antenna system.

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Jedno i više elementne mikrotrakaste monopolne antene Minkowskog za pokretne komunikacijske uređaje. U radu je prikazana fraktalna monopolna antena Minkowskog. Ova je antena namijenjena pokretnim komunikacijskim uređajima s jednom ili više antena. U slučaju primjene jedne antene proučen je utjecaj njezinog položaja u odnosu na osnovnu vodljivu ravninu i predložen je postupak za fino ugađanje sustava u uvjetima najgoreg slučaja. Istražen je i utjecaj izmjera osnovne vodljive ravnine na ulaznu impedanciju antene i na njezine dijagrame zračenja te su izvedeni općeniti zaključci. Zatim je istražen i antenski niz od četiri takva elementa. Proučavane su karakteristike niza kada se niz koristi u uvjetima diverzitija. Karakteristike diverzitija vrednovane su pomoću korelacijskog koeficijenta anvelope, srednjeg efektivnog dobitka i efektivnog dobitka diverzitija. Razmotren je i utjecaj međusobne sprege antena na ukupne karakteristike antenskog sustava.

Ključne riječi: antenski diverziti, dobitak diverzitija, fraktalna antena, utjecaj osnovne vodljive ravnine, Minkowski, monopolna antena

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Received: 2004–10–23